e.m. waves

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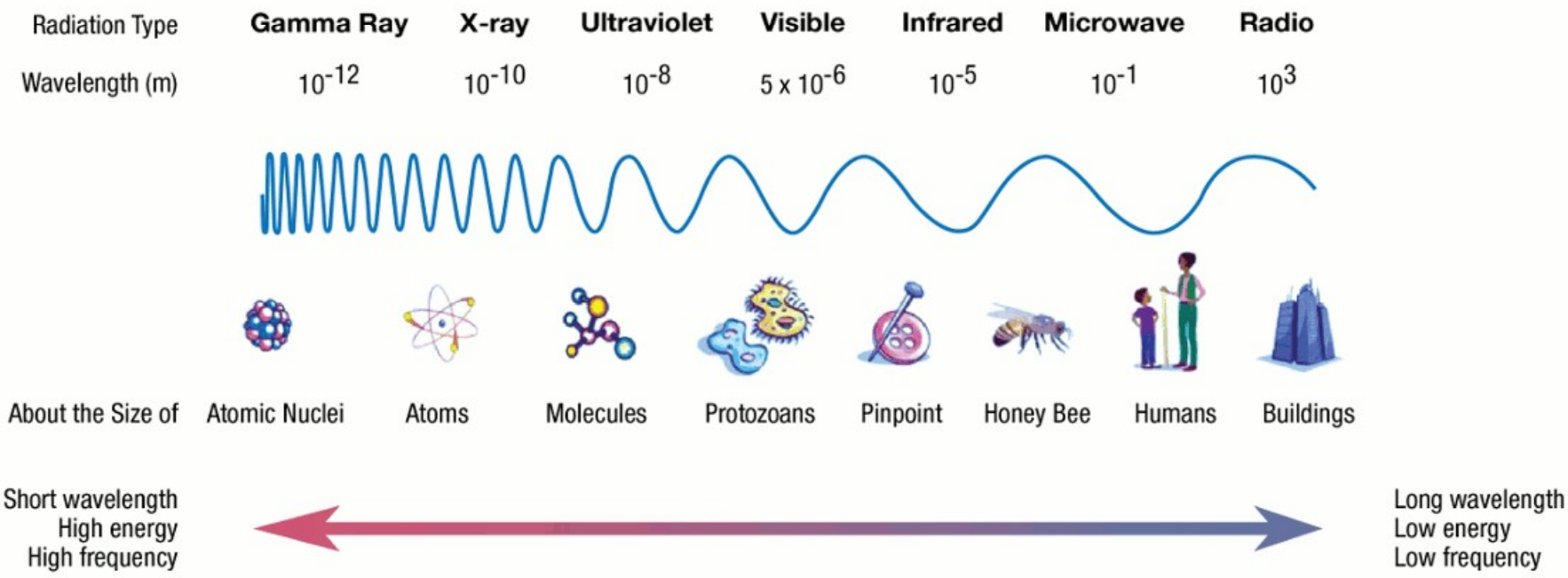
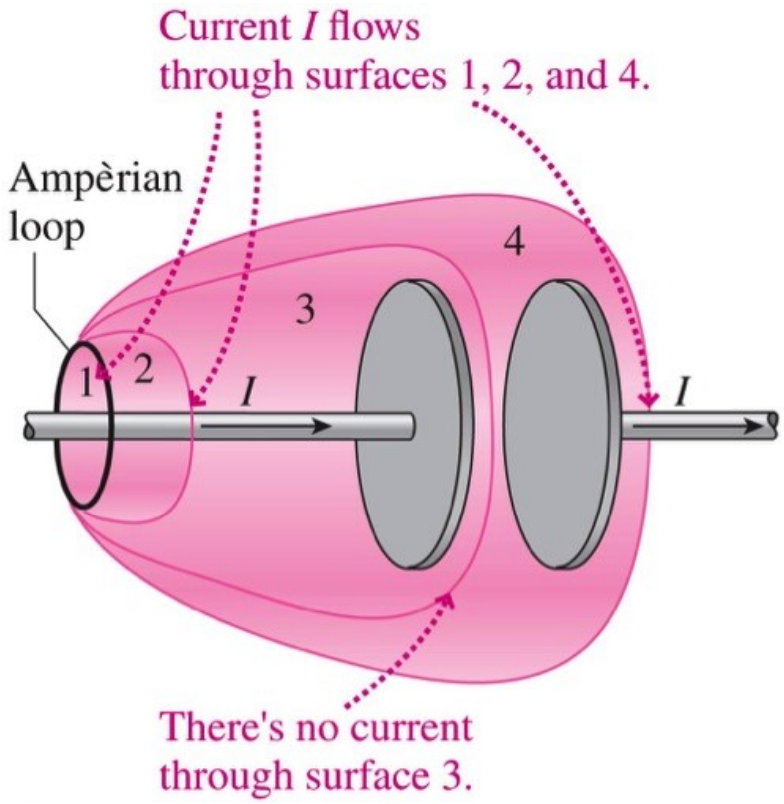


Displacement current

Current resulting in change (displacement) of electric field



Total current in Ampere's loop law is sum of conduction current (i_C) and displacement current (i_D)

$$\oint B \bullet dl = \mu_o i_c + \mu_o \varepsilon_o \frac{d\phi_E}{dt}$$

Ampere-Maxwell law

With the introduction of displacement current the electromagnetic phenomena are more *symmetric* as changing magnetic field results in electric field and changing electric field results in magnetic field.

General observations of charges and fields

- Stationary charges produce electric fields
- Charges in uniform motion produce magnetic field and electric field that is constant in time and space.
- Accelerated charges produce time varying electric and magnetic fields
- Oscillating electric field produces oscillating magnetic field and vice-versa.
- Frequency of generated e.m. wave is equal to frequency of the source.
- Energy associated with e.m. wave comes at the expense of energy of oscillating charge.

General properties of *e.m.* waves

- em waves are non- mechanical waves
- em waves are transverse waves (as they exhibit polarization)
- em waves undergo superposition
- em waves exhibit reflection, refraction, transmission, absorption etc.
- e.m. waves carry energy and momentum
- e.m. waves exert radiation pressure

e.m. wave equation

Equation for $\boldsymbol{E}$ and $\boldsymbol{B}$ for an e.m. wave propagating along the z-axis

$$E_x = E_o \sin(kz - \omega t) \qquad B_y = B_o \sin(kz - \omega t)$$

E_o is amplitude of electric field intensity

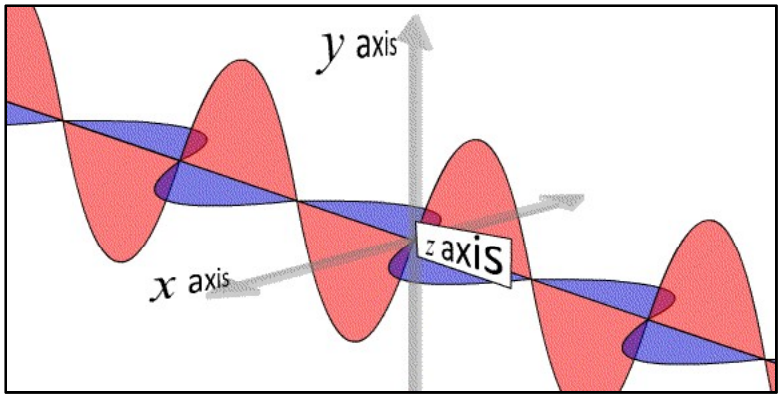
B_o is amplitude of magnetic field induction

k : propagation constant

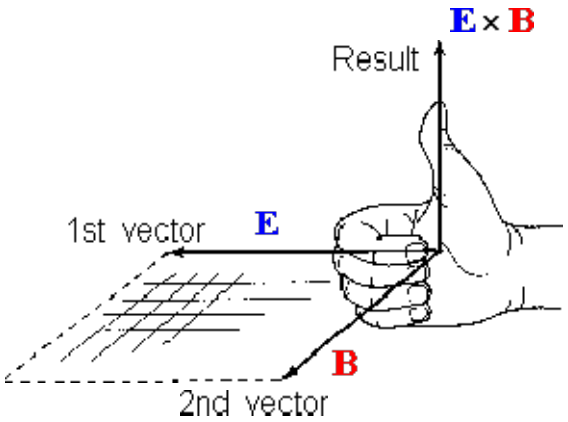
z : position

ω : angular frequency

t : instant of time



$$k = \frac{2\pi}{\lambda}$$



$\boldsymbol{E}$, $\boldsymbol{B}$ and direction of propagation are mutually perpendicular to each other.

Important relations

ω, speed and k relation $\omega = ck$

Speed of propagation in vacuum $c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$

Speed of propagation in a medium $v = \frac{1}{\sqrt{\mu \varepsilon}}$

Refractive index of medium $\sqrt{\mu_r \varepsilon_r}$

Amplitudes relation $B_o = \frac{E_o}{c}$

ω : angular frequency

k : wave vector

c : speed of light in vacuum

μ_o : permeability of vacuum

ε_o : permittivity of vacuum

v : speed of flight in a medium

μ : permeability of medium

ε : permittivity of medium

E_o : Electric field intensity amplitude

B_o : Magnetic field amplitude

Energy considerations in *e.m.* waves

- Energy density associated with electric field in *e.m.* wave is $\frac{\varepsilon_o E^2}{2}$
- Energy density associated with magnetic field in *e.m.* wave is $\frac{B^2}{2\mu_o}$

Note : E and B in above relations are the instantaneous values and not the peak values

- Average Energy density due to $\boldsymbol{E}$ is equal to average energy density due to $\boldsymbol{B}$
- Total energy density associated with electric & magnetic field in *e.m.* wave is $\varepsilon_o E^2$ or $\frac{B^2}{\mu_o}$
- The maximum rate of energy flow is $\frac{1}{\mu_o}\boldsymbol{E}\times\boldsymbol{B}$

Momentum transfer in *e.m.* waves

If total energy transferred in time t is U then the total momentum delivered to the surface is

(a) assuming complete absorption $p = \frac{U}{c}$

(b) assuming complete reflection $p = \frac{2U}{c}$

Broad components of electromagnetic spectrum

Radio waves

- Produced by accelerated motion of charges in conducting wires
- Frequency range 500 kHz to 1000 MHz
- Used in communication (AM, FM cellular and TV)

Microwaves

- Short wavelength radio waves produced by special vacuum tubes
- Frequency range in GHz
- Used in radar systems and air navigation
- Microwave oven : Frequency of microwaves is adjusted to match the resonant frequency of water molecules to maximize transfer of energy (therefore efficient heating)

Broad components of electromagnetic spectrum

Infrared waves

- Produced by bodies at high temperature
- Also commonly called heat waves
- IR lamps are used for heat therapy, IR radiation keeps earth surface warm (green house effect)
- IR radiation emitting LEDs are used for remote

Visible rays

- 4×10^{14}Hz to 7×10^{14}Hz
- Wavelength range 400 nm to 700 nm

Broad components of electromagnetic spectrum

UV rays

- Produced by special lamps and very hot bodies
- Wavelength range 400 nm to 0.6 nm
- Most of UV radiation is absorbed by ozone and ordinary glass
- UV rays cause tanning of skin.
- Used for eye surgery and killing germs in purification of water.

X rays

- Obtained by bombarding heavy metal targets by high energy electrons

γ rays

- Produced in nuclear reactions

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